Fish life history and habitat use in the Northwest Territories: round whitefish (*Prosopium cylindraceum*)

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FISH LIFE HISTORY AND HABITAT USE IN THE NORTHWEST TERRITORIES: ROUND WHITEFISH (*Prosopium cylindraceum*)

by

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Round whitefish occur throughout the Northwest Territories, where populations can follow lacustrine, adfluvial, fluvial, or anadromous life histories. Differences in habitat use by these populations and in the seasonal requirements of eggs, fry, juveniles, and adults are summarized. The round whitefish prefers lake, river and larger stream (>10 m width) habitats, eats mostly aquatic invertebrates, and spawns in the fall in either river or lake habitats. It is common in cold, clear water (0 to 18°C) above 37 m depth, but sometimes uses turbidity for cover. To support the assessment, avoidance and mitigation of environmental impacts in the Mackenzie River Valley, the potential impacts of development activities and climate change on survival of the species are reviewed. The species' small size, dietary preferences, limited seasonal movements and use of lakes or rivers for spawning may limit its vulnerability to habitat degradation, habitat fragmentation, harvesting, and climate change. However, its eggs are sensitive to elevated or unstable temperatures during incubation. It is absent from lakes with a pH of less than 5.5. And, the introduction of warm-water predators such as smallmouth bass (*Micropterus dolomieu*), yellow perch (*Perca flavescens*), and rainbow smelt (*Osmerus mordax*) can cause populations to decline.

Key words: distribution; life history; habitat requirements; seasonal movements; reproduction; spawning; rearing; life cycle; Mackenzie watershed; hydrological integrity; fresh water; Coregonidae.

RÉSUMÉ

Stewart, D.B., Carmichael, T.J., Sawatzky, C.D., Mochnacz, N.J., and Reist, J.D. 2007. Fish life history and habitat use in the Northwest Territories: round whitefish (*Prosopium cylindraceum*). Can. Manuscr. Rep. Fish. Aquat. Sci. 2795: vi + 37 p.

Le ménomini rond est présent dans toutes les eaux des Territoires du Nord-Ouest, où les populations peuvent être de nature lacustre, adfluviale, fluviale ou anadrome. Nous résumons ici les différences dans l'utilisation des habitats par ces populations et dans les besoins saisonniers des œufs, des alevins, des juvéniles et des adultes. Le ménomini rond préfère les lacs, les rivières et les grands ruisseaux (> 10 m en largeur) et se nourrit principalement d'invertébrés aquatiques. Il fraye à l'automne en milieu fluvial ou lacustre. On le trouve communément dans les eaux froides et claires (0 à 18°°C) à des profondeurs inférieures à 37 m, mais il se dissimule parfois en eau turbide. Nous examinons les incidences éventuelles des activités humaines et du changement climatique sur la survie de l'espèce en appui de l'évaluation, de l'évitement ou de l'atténuation des incidences environnementales dans la vallée du Mackenzie. La petite taille de l'espèce, ses préférences alimentaires, ses déplacements saisonniers limités et son utilisation des lacs et des rivières pour la fraie peuvent limiter sa vulnérabilité à la dégradation et à la fragmentation de l'habitat, à la récolte et au changement climatique. Toutefois, ses œufs sont sensibles aux températures élevées ou instables au cours de l'incubation. Il est absent des lacs dont le pH est inférieur à 5,5. De plus, l'introduction de prédateurs d'eau tempérée, tels l'achigan à petite bouche (*Micropterus dolomieu*), la perchaude (*Perca flavescens*) et l'éperlan (*Osmerus mordax*), peut entraîner un déclin des populations.

Mots principaux : répartition; cycle vital; exigences en matière d'habitat; déplacements saisonniers; reproduction; fraie; alevinage; bassin versant du Mackenzie; intégrité hydrologique; eau douce; Corégonidés.

1.0 INTRODUCTION

Renewed interest in natural gas pipeline development along the Mackenzie Valley has raised the prospect that fish species in the watershed may be impacted by changes to their habitat. The proposed pipeline would extend from near the Beaufort Sea coast to markets in the south (http://www.mackenziegasproject.com/). Fishes in the Mackenzie River depend upon the integrity of their aquatic habitats, so it is important to summarize knowledge that can be used to assess potential impacts of this development proposal and others, and to facilitate efforts to avoid and mitigate these impacts.

This report reviews knowledge of the round whitefish, *Prosopium cylindraceum* (Pennant, 1784). While it is common in Canada's northern lakes and rivers the round whitefish is one of the least studied coregonines, in part because of its slow growth and small average size which limit the species' commercial value (Koelz 1929; Mraz 1964; MacKay and Power 1968). Information is provided on the species' distribution, habitat use during the various stages of its life history, and about threats posed to the species and its habitat by development activities. Where gaps in knowledge of the species in the Northwest Territories are identified, supplementary information is included where possible from other regions. This information was compiled to assist developers, habitat managers, and researchers. Similar reports have been prepared for other fishes that inhabit the Mackenzie River watershed.

1.1 Taxonomic units

Separate taxonomic units have not been demonstrated for round whitefish, although McPhail and Lindsey (1970) suggested that two morphological types might exist in North America because of the apparent discontinuity of the species' Canadian distribution. The existence of geographically separate breeding stocks is likely in the Mackenzie Valley due to the species' wide distribution, but these fish have not been examined for genetic differences.

1.2 Distribution

The round whitefish is widely distributed in Siberia and on the northern mainland of North America (Hale 1981). It occurs throughout the mainland of Alaska, Yukon and the Northwest Territories; in northern British Columbia; and throughout all but the northeastern corner of the Nunavut mainland (Figure 1) (McPhail and Lindsey 1970; Scott and Crossman 1973; Stein *et al.* 1973b; Hatfield *et al.* 1978; Lawrence *et al.* 1978; Macdonald and Fudge 1979; Lee *et al.* 1980; MacDonald and Stewart 1980; Stewart and Bernier 1983, 1984; Sawatzky *et al.* 2007). It is common in the Mackenzie Valley and occurs in all ecozones of the Northwest Territories (Marshall and Schut 1999).

Moving eastward there appears to be a gap in the species' distribution, with few reports of its occurrence between northwestern Manitoba and Lake Nipigon, ON. It is distributed downstream of Lake Nipigon in southern Ontario, Quebec, New Brunswick and several New England states, and is common in northern Quebec and Labrador.

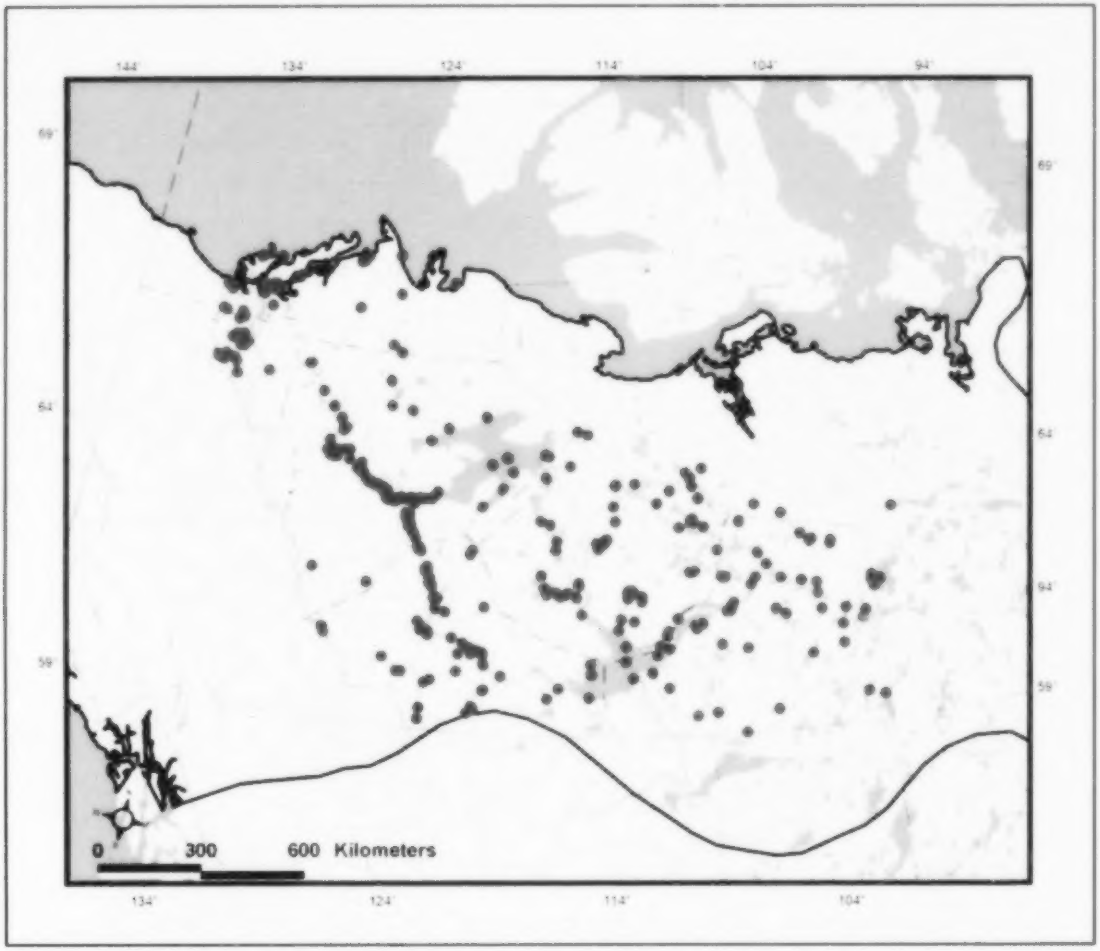

Figure 1. Round whitefish distribution in the Northwest Territories (updated from Sawatzky *et al.* 2007).

2.0 LIFE HISTORY TYPES

Round whitefish shows **lacustrine**[1] (Koelz 1929; Normandeau 1969; Bryan and Kato 1975), **fluvial**, **adfluvial** (Kra'sikova 1968; Goodyear *et al.* 1982), and **anadromous** (Morin *et al.* 1982) life history types (Table 1). In the southern part of their range, these fish are usually found in shallower areas of deep lakes, and in northern

[1] Terms in bold type are defined in the Glossary.

Table 1. Habitat use by round whitefish populations with different life history types.

HABITAT	POPULATION			
	FLUVIAL	ADFLUVIAL	LACUSTRINE	ANADROMOUS
Tributary streams with channel widths >10 m	• Spawning and rearing habitat. • Feeding habitat for all life stages. • Overwintering habitat for eggs and possibly other life stages. • Migratory corridors for fry, juveniles and adults.	• Spawning and rearing habitat. • Feeding habitat for all life stages. • Overwintering habitat for eggs and possibly other life stages. • Migratory corridors for fry juveniles and adults.		• Spawning and rearing habitat. • Feeding habitat for all life stages. • Overwintering habitat for eggs and possibly other life stages. • Migratory corridors for fry, juveniles and adults.
Rivers	• Spawning and rearing habitat. • Feeding and overwintering habitat for all life stages. • Migratory corridors for fry, juveniles and adults.	• Spawning and rearing habitat. • Feeding and overwintering habitat for all life stages. • Migratory corridors for fry, juveniles and adults.	• Spawning and rearing habitat at stream inlets or lake outlets.	• Spawning and rearing habitat. • Feeding and overwintering habitat for all life stages. • Migratory corridors for fry, juveniles and adults.
Lakes	• Possible migration corridors.	• Feeding and overwintering habitat for juveniles and adults.	• Year-round use for all activities by all life stages.	• Spawning and rearing habitat. • Feeding and overwintering habitat for all life stages. • Migratory corridors for juveniles and adults.
Brackish estuaries				• Summer feeding habit for some adults and juveniles.

parts may also be found in rivers and streams (Scott and Crossman 1973). They enter brackish waters off the Mackenzie and Coppermine rivers (McPhail and Lindsey 1970; Scott and Crossman 1973), in Prudhoe Bay Alaska (Bendock 1977), and along the coasts of Hudson and James bays (Dymond 1933; McAllister 1964; Morin *et al.* 1980).

In Alaska, round whitefish were typically present in lakes with second order or higher outlet streams and absent from those with poorer connections (Hershey *et al.* 2006). This suggests that factors affecting lake colonization may be more important than those causing extinction. Surrogate variables that were also important relative to lake order, included maximum stream gradient, lake altitude, lake perimeter, and shoreline development (Hershey *et al.* 2006). Higher order streams or their inlets or outlets may also be important for providing spawning habitat.

The physical parameters that best predicted round whitefish presence in Ontario and New York lakes were pH, growing degree-days, and surface area to depth ratio (Olden and Jackson 2002; Olden 2003; Steinhart *et al.* 2007). The likelihood of round whitefish being present in a lake declined with declining pH (absent below 5.5) and with increases in the surface area to depth ratio, growing degree-days, and number of warm water predators.

3.0 LIFE HISTORY STAGES AND HABITAT USE

Key transitions in the round whitefish life history are illustrated schematically in Figure 2 and discussed below. Habitat use by round whitefish has seldom been the focus of detailed studies. However, data have been collected during general baseline studies or studies concentrating on other species (Table 2, Table 3). Life history and habitat parameters in the discussion that follows are defined in Appendix 1. Stream and lake habitat requirements are summarized in Appendix 2 and Appendix 3, respectively.

3.1 Eggs (Spawning and incubation habitat)

Round whitefish spawn more than once following maturity **(iteroparous)** (Kra'sikova 1968; McCart *et al.* 1972; Craig and Wells 1975), but not necessarily every year (Jessop and Power 1973). Spawning occurs in lakes (Koelz 1929; Mraz 1964; Armstrong *et al.* 1977; Normandeau 1969; Becker 1983; Haymes and Kolenosky 1984), sometimes at lake outlets (Bryan and Kato 1975) or river mouths (Koelz 1929), and in rivers and streams (McPhail and Lindsey 1970; Becker 1983; Suchanek *et al.* 1984; Zyus'ko *et al.* 1993). Spawning locations have not been identified in the Mackenzie Valley.

Spawning migrations may be undertaken by some round whitefish populations. Fish that move into the Rat River, NT (Jessop *et al.* 1973) and into tributaries of Alaska's Sagavanirktok River (Hale 1981) in late August and September, prior to the spawning season, may be part of upstream spawning runs. Fish may also run into small tributaries of the Great Lakes to spawn (Koelz 1929).

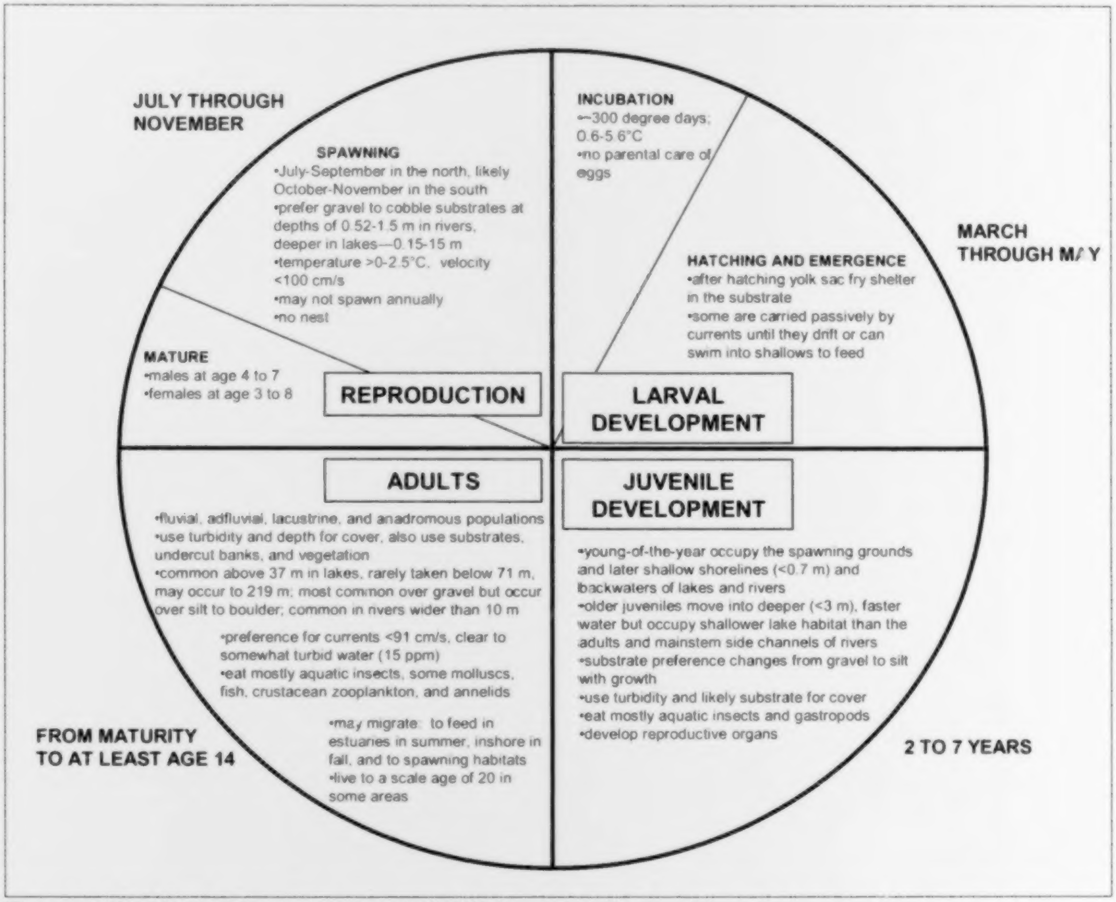

Figure 2. Generic life cycle of round whitefish.

The timing of round whitefish spawning varies geographically, likely in response to seasonal differences in water temperatures among waterbodies. Fish in the northern Mackenzie Valley spawn in the summer while those in southern Canada spawn in late fall or early winter. In the Northwest Territories, ripe and spent males have been taken in Great Bear Lake on 6 July (Falk and Dahlke 1974), and ripe and running males have been taken in its Sloan River tributary on 18 August (Stewart and MacDonald 1978). Ripe fish have also been caught at the Rat River in August and early September (Jessop *et al.* 1973).

Table 2. Observed habitat use by round whitefish (data from NT populations in bold type; numbers in brackets refer to sources cited below).

HABITAT FEATURES		LIFE STAGE			
		Spawn/egg	**Young of the year**	**Juvenile**	**Adult**
Habitat type		Lake shores and reefs, often in areas with current near lake outlets, river inlets, or points (2, 5-9); rivers and streams (4, 8, 10, 11)	On spawning grounds, shallow shorelines, backwaters (2, 21, 24)	Same as adults but shallower (18), mainstem side channels (24)	Shallow waters of deep lakes having 2nd order or higher stream connections (5, 12, 18, 27, 38-40); tributary mouths and main and side channel habitats, deeper pools, and rapids of larger rivers (41-43), sometimes estuaries (44-47)
Stream gradient					1.3 to 14.2 m/km (18)
Depth range (m)		Lake: 0.15-15 (4, 5, 11, 48) River: 0.52-1.5 (4, 11, 23)	River: <0.7 on average (24)	River: up to 3 m, with strong preference for depths <0.15 m by small fish (11)	Lake: **most taken in upper 37 m, rarely taken below 71 m** (5, 12, **27**, **38**, 40)
Substrate		Mostly over gravel to cobble, sometimes over silt to boulder or vegetation (2-5, 11)	Initial preference for fine gravel changes to silt with growth, but found over substrates ranging from silt to boulder (13, 20, 24)		River: silt to boulder but most common over gravel (18)
Cover			Rubble and boulders, vegetation sometimes present but not used (2, 24)	River: Turbid water (>30 NTU) (11)	River: Turbidity and depth and from most to least preferred: cobble and boulders, undercut banks, overhanging vegetation, debris, aquatic vegetation, rubble and large gravel (11)
Velocity range (cm/s)		0-100 cm/s (3-5, 11)	0-37 cm/s (24)	Low (11)	17 to 91 cm/s preferred (11, 42)
Turbidity (NTU)	Range	River: 2 to 14 NTU (11)		River: >30 NTU water used for cover (11)	Clear to 15 ppm (18)
	Limits				
Oxygen (ppm)	Range				River: 49-100% saturation; healthy at 2.6 ppm (18)
	Limits				
Temperature (°C)	Range	Spawning: >0-2.5°C in north (3, 4, 11); 2.2-4.5°C in south (2, 9, 12) Incubation: ~300 degree days; 0.6-5.6°C (2, 11, 13)			0°C to at least 22°C (18, 55)
	Limits				

Prey items	Primary	-	Aquatic insect larvae (24)	**Aquatic insects** (29)	**Aquatic insects** (7, **22**, 24, **25**, **27**, **29**, **38**, 51, 52, **53**, **54**)
	secondary	-	Water mites (24)	**Gastropods** (29)	**Molluscs, fish, crustacean zooplankton, annelids** (7, **22**, 24, **25, 27, 29, 38**, 51, 52, **53, 54**)
Period		Spawning: **NT Jul.-Sept.** (**1, 14-17**); AK, YT, NU Sept.-Nov. (3, 4, 11, 18, 19); NH and Gt. Lakes Nov.-Dec. (2, 5, 9, 13, 20) Incubation: From spawning to May in Alaska (22) or Mar. to May in NH and the Great Lakes (13, 21, 22)	Fry emergence: Apr.-**June** (2, 21, **22, 23**); first year.	Female: **2 to 7 y**, Male: **3 to 6 y** (**22, 25-29**); similar in NU, YT, and AK (30-33); earlier in QC (34-36) and the Great Lakes (6, 7, 9, 37)	Female: **6 to 11 y**, Male: **7 to 10 y** (**22, 25-29**)
Size/age range (Note: fish are considered to be age 0 until December 31 of the year they are hatched)		Egg diameter: Unfertilized: mean 2.7 mm dia (range 2.4-2.95 mm) (2) Water hardened: 3.10 to 4.60 mm (2,3,4) Redds: none	12 mm TL at emergence (8, 21), 63-99 mm FL in late August (23, 24)	Female: **age 3 to 8**, Male: **age 4 to 7** (**22, 25-29**); similar in NU, YT, and AK (30-33); younger in QC (34-36) and the Great Lakes (6, 7, 9, 37)	Maximum: **age 14, 561 mm TL, 2.0 kg** (**38, 50**); **530 mm FL** (**1**); 20 y (49)

1 = Jessop *et al.* 1973—Rat River, NT
2 = Normandeau 1969—Newfound Lake, NH
3 = Bryan and Kato 1975—Aishihik Lake, YT
4 = Zyus'ko *et al.* 1993—Torgo River, Siberia
5 = Koelz 1929—Great Lakes
6 = Mraz 1964—Lake Michigan
7 = Armstrong *et al.* 1977—Lake Michigan
8 = Becker 1983—Review Wisconsin
9 = Haymes and Kolenosky 1984—Lake Ontario
10 = McPhail and Lindsey 1970—NW Canada and AK
11 = Suchanek *et al.* 1984—Susitna River, AK
12 = Scott and Crossman 1973—review
13 = McKinley 1983—Lake Ontario
14 = Falk and Dahlke 1974—Great Bear Lake, NT
15 = Stewart and MacDonald 1978—Sloan River, NT
16 = Shotton 1971—Waters River, YT
17 = MacDonald and Fudge 1979—Kaminak lake, NU
18 = Hale 1981—Review Alaska
19 = Harper 1948—Nueltin Lake, NU
20 = McKinley 1984—Lake Ontario
21 = Shestakov 1991, 1992—Anadyr River, Siberia
22 = Chang-Kue and Cameron 1980—Great Bear R., NT
23 = Walker 1983—Chena River, AK
24 = Lee 1985—Chena River, AK
25 = Jessop *et al.* 1993—Indin Lake, NT
26 = Read and Roberge 1986—Noell Lake, NT
27 = Kennedy 1949—Great Bear Lake, NT
28 = Dunn and Roberge 1989—Great Bear Lake, NT
29 = Stein *et al.* 1973b—Mackenzie R. watershed, NT
30 = Roberge *et al.* 1984—lakes in Kivalliq region of NU
31 = Roberge and Dunn 1985—Mosquito Lake, NU
32 = Horler *et al.* 1983—Yukon lakes
33 = Pearse 1974—Delta Clearwater River, Alaska
34 = Morin *et al.* 1982—La Grande River, QC
35 = MacKay and Power 1968—Kokosak & George r., QC
36 = Jessop and Power 1973—Leaf River, QC
37 = Bailey 1963—Lake Superior
38 = Rawson 1951—Great Slave Lake, NT
39 = Hershey *et al.* 2006—Alaskan lakes
40 = Balesic 1983—Lake Huron
41 = Mecum 1984—Tanana River, Alaska
42 = Den Beste and McCart 1984—Alaskan interior rivers
43 = Kemp *et al.* 1989--Petite rivière de la Baleine, QC
44 = Morin *et al.* 1980—Quebec coast
45 = Morin and Dodson 1986—Quebec coast
46 = Le Jeune and Shooner 1982--Grande rivière de la Baleine and Petite rivière de la Baleine, QC
47 = St. Arsenault *et al.* 1982--ditto
48 = Carey 1983—Lake Ontario
49 = Moshenko 1980—Macdougall Lake, NU
50 = Keleher 1961—Great Slave Lake, NT
51 = Magnin and Clément 1979—La Grande River, QC
52 = Merrick *et al.* 1992—Toolik Lake, Alaska
53 = Martin 2001—Lac du Gras area, NT
54 = Chang-Kue *et al.* 1987—Rivière la Martre, NT
55 = Sandercock 1964—lakes in Algonquin Park, ON
56 = Bendock 1980—Colville River, AK

Table 3. Habitat and life history parameters related to round whitefish reproduction, with data from the NT in bold type. Numbers in brackets refer to data sources listed below.

PARAMETER	LAKE or RIVER (Data source)
Reproductive strategy:	**Iteroparous** (4)
Age at maturity:	Female: **age 3 to 8** (**10-12**) Male: **age 4 to 7** (**10-12**) Sex unknown: **age 6-8** (**1, 7, 9**)
Fecundity (eggs/female):	Mean: 5,000 to 12,000 (14-17, 30, 31) Range: 1,000 to 25,000 (14-17, 30, 31)
Spawning:	May not occur annually following maturity (4, 17)
Habitat type	Lake shores and reefs, often in areas with current near lake outlets, river inlets, or points (15, 18, 20-23); rivers and streams (3, 5, 17, 19, 22)
Builds nest	No. Substrate not disturbed (2, 5)
Temperature (°C)	Spawning: >0-2.5°C in north (2, 17, 19); 2.2-4.5°C in south (15, 23, 24) Incubation: ~300 degree days; 0.6-5.6°C (15, 19, 25)
Depth (m)	Lake: 0.15-15 (17-19, 27) River: 0.52-1.5 (17, 19, 26)
Substrate	Gravel to cobble, sometimes over silt to boulder or vegetation (2, 15, 17-19)
Current velocity (cm/s)	0-100 cm/s (2, 17-19)
Maximum age:	Scales: **age 14** (**6, 29**); 20 (28); Otoliths: age 22 (30)
Age at senescence:	Unknown

1 = Stein *et al.* 1973a—Mackenzie River watershed, NT
2 = Bryan and Kato 1975—Aishihik Lake, YT
3 = Sundet and Wegner 1983—Susitna River, AK
4 = Jessop and Power 1973—Leaf River, QC
5 = McPhail and Lindsey 1970—NW Canada and AK
6 = Rawson 1951—Great Slave Lake, NT
7 = Chang-Kue and Cameron 1980—Great Bear River, NT
8 = Jessop *et al.* 1993—Indin Lake, NT
9 = Read and Roberge 1986—Noell Lake, NT
10 = Kennedy 1949—Great Bear Lake, NT
11 = Falk and Dahlke 1974—Great Bear Lake, NT
12 = Dunn and Roberge 1989—Great Bear Lake, NT
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14 = Bailey 1963—Lake Superior
15 = Normandeau 1969—Newfound Lake, NH
16 = Pearse 1974—Richardson Clearwater River, AK
17 = Zyus'ko *et al.* 1993—Torgo River, Siberia
18 = Koelz 1929—Great Lakes
19 = Suchanek *et al.* 1984—Susitna River, AK
20 = Mraz 1964—Lake Michigan
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22 = Becker 1983—Review Wisconsin
23 = Haymes and Kolenosky 1984—Lake Ontario
24 = Scott and Crossman 1973—Review Canada
25 = McKinley 1983—Lake Ontario
26 = Walker 1983—Chena River, AK
27 = Carey 1983—Lake Ontario
28 = Moshenko 1980—Macdougall Lake, NU
29 = Keleher 1961—Great Slave Lake, NT
30 = Craig and Wells 1975—Chandalar River, AK
31 = Kra'sikova 1968—Noril'sk Lake and River system, Siberia

Summer spawning has also been observed in the Yukon, where Shotton (1971) caught both near gravid and spent females in the Waters River on 19 July, and in Nunavut, where MacDonald and Fudge (1979) caught ripe and spent male and female round whitefish at Kaminak Lake in the eastern Kivalliq Region in early July. Fallspawning has been observed in some northern waters. In Alaska it has been observed in late September through early November (Pearse 1974; Craig and Wells 1975; Bendock 1980; Hale 1981; Suchanek *et al.* 1984; Sundet and Wenger 1984); at Aishihik Lake, Yukon in November (Bryan and Kato 1975); in Nueltin Lake, Nunavut, it probably occurs in October and November (Harper 1948); and in Siberia's Torgo River it begins in early October (Zyus'ko *et al.* 1993). Early winter spawning is typical in waters near the southern limit of the species' distribution. In the Great Lakes, round whitefish spawn in late November to mid December (Koelz 1929; Scott and Crossman 1973; McKinley 1983, 1984; Haymes and Kolenosky 1984), and in Newfound Lake, New Hampshire they spawn in the first three weeks of December (Normandeau 1969). Spring spawning may occur on occasion, since a single ripe female was taken in May during the spawning period of Arctic grayling (*Thymallus arcticus*) at a water temperature of 4-6°C (Zyus'ko *et al.* 1993).

Males usually arrive on the spawning ground before the females (Normandeau 1969), and before spawning the fish swim near the bottom in male-female pairs or small groups (Normandeau 1969; Bryan and Kato 1975). Nuptial tubercles are well developed on the first 5 rows of scales above and below the lateral line in males, less so in females (Scott and Crossman 1973). Eggs are broadcast over the substrate, without any nest building or parental care (McPhail and Lindsey 1970; Bryan and Kato 1975). In Aishihik Lake, Yukon, round whitefish spawned during the day (Bryan and Kato 1975).

Spawning in northern waters typically takes place at water temperatures less than 2.5°C. In Alaska's Susitna River, water temperatures during spawning were close to 0°C, with intergravel temperatures of 0.6°C (Suchanek *et al.* 1984). In Aishihik Lake, Yukon, water temperatures during spawning were 0.8 to 2.2°C (Bryan and Kato 1975). Round whitefish in Siberia's Torgo River began spawning at a water temperature of 2.5°C or less, just before or as slush ice began to form (Zyus'ko *et al.* 1993). Somewhat warmer temperatures have been observed during spawning in southern lakes: 2.2°C at Newfound Lake, NH (Normandeau 1969); <3°C in Lake Ontario (Haymes and Kolenosky 1984), and 4.5°C at Lake Superior (Scott and Crossman 1973).

Round whitefish often spawn in shallow water, but may spawn at depths of up to 15 m. Shallow-water spawning has been observed in the north in both lake and river habitats. Round whitefish in Aishihik Lake, YT, spawned at depths of 0.70 to 2.50 m (Bryan and Kato 1975). At the Susitna River in Alaska, fish spawned at depths of 0.52 to 1.28 m (Suchanek *et al.* 1984), while those in Siberia's Torgo River spawned at depths of 1.0 to 1.5 m (Zyus'ko *et al.* 1993). Further south, round whitefish in

oligotrophic Newfound Lake, NH, spawned at depths of 0.15 to ~3.66 m, although most eggs were found between 0.15 and 0.6 m (Normandeau 1969). Lake trout spawned over the same reef but earlier in the season (October). Spawning in the Great Lakes typically occurs at depths of 4 to 15 m, with gillnet catches suggesting preference for headland areas and water depths of 5 to 10 m (Koelz 1929; Scott and Crossman 1973; Carey 1983; Haymes and Kolenosky 1984).

Spawning typically takes place over gravel to cobble substrates (Koelz 1929; Normandeau 1969; Bryan and Kato 1975; Suchanek *et al.* 1984; Sundet and Wenger 1984; Zyus'ko *et al.* 1993), although it has been observed over boulders and over sand and silt substrates in areas with emergent vegetation (Bryan and Kato 1975; Suchanek *et al.* 1984; Sundet and Wenger 1984; Zyus'ko *et al.* 1993). In Aishihik Lake, YT, eggs were broadcast over substrates ranging from silt to boulders, and on *Potamogeton*, but were most abundant over gravel to cobble substrates (particle size 0.2-25 cm) (Bryan and Kato 1975). Spawners did not disturb the substrates.

Spawning is common in areas with a discernible current, such as a river channel (Suchanek *et al.* 1984; Zyus'ko *et al.* 1993), lake outlet (Bryan and Kato 1975) or stream mouth (Koelz 1929), or lake reef that is exposed to wind driven currents (Normandeau 1968). It also occurs in still water (Koelz 1929). In Aishihik Lake, YT, spawning occurred in currents ranging from 63 cm/s to less than 31 cm/s (Bryan and Kato 1975). The density of eggs per unit area was greatest in the faster current at depths of less than 1 m. Spawning occurred in current velocities of 12 to 55 cm/s in the Susitna River of Alaska (Suchanek *et al.* 1984), and of up to 50 to 100 cm/s in Siberia's Torgo River (Zyus'ko *et al.* 1993).

Turbidity at the spawning sites in Alaska's Susitna River ranged from 2 to 14 NTU (Suchanek *et al.* 1984). Relatively high specific conductance (160 µmhos/cm) at one site suggested that fish were using an area with groundwater upwelling (Sundet and Wenger 1984).

Unfertilized eggs are small, yellow and average 2.7 mm in diameter (range 2.4 to 2.95 mm) (Normandeau 1969). Newly laid eggs sink to the bottom and absorb moisture, expanding to between 3.10 and 4.60 mm in diameter (Newfound Lake, NH: mean=3.94 mm, range 3.30 to 4.60 mm--Normandeau 1969; Aishihik Lake, YT: range 3.14 to 3.44 mm--Bryan and Kato 1975; Torgo River, Siberia: range 3.10 to 3.25 mm—Zyus'ko *et al.* 1993). Drifting eggs were captured more frequently during the day than at night in Aishihik Lake, YT (Bryan and Kato 1975). In Siberia's Torgo River they were carried downstream and dispersed by the turbulent flow to drop onto a slushy bottom where they were held by ice crystals and in the spaces between rocks (Zyus'ko *et al.* 1993). Further development may occur in the ice. The egg membrane is not adhesive.

Fecundity varies with size, with the smallest females producing only about 1,000 eggs and the largest up to 25,000 eggs (Table 4)(Bailey 1963; Kra'sikova 1968; Normandeau 1969; McCart *et al.* 1972; Pearse 1974; Craig and Wells 1975; Zyus'ko *et al.* 1993). On average, females likely produce between 5,000 and 12,000 eggs during a spawning year. Morin *et al.* (1982) described the relationship between body weight and fecundity as: $y = 1.179+0.934x$, where x is the logarithm of the net weight in grams (i.e., total weight less ovaries) and y is the logarithm of fecundity ($n = 18$, $r = 0.73$; $P<0.01$).

Table 4. Round whitefish fecundity.

Location	Sample size	Length/ scale age	Fecundity (eggs/female)		Reference
			Mean	Range	
Lake Superior	37	267-435 mm TL	5,330	1,076 - 10,187	Bailey 1963
Noril'sk Lake and River system, Siberia	36	~365-477 mm, age 7-10	-	4,600 - 14,300	Kra'sikova 1968
Rybnaya stream, Siberia	6	age 7-10	10,500	5,800 - 13,600	Kra'sikova 1968
Newfound Lake, NH	48	age 3 - 8	-	2,200 - 9,445	Normandeau 1969
Galbraith Lake, AK		319-413 mm FL	6,297	2,862 - 10,946	McCart *et al.* 1972
Richardson Clearwater River, AK	4	-	12,529	9,145 - 17,010	Pearse 1974
Chandalar River, AK	9	313-413 mm FL	10,300	4,200 - 18,700	Craig and Wells 1975
Torgo River, Siberia	34	310-485 mm FL age 4-13	-	3,087 - 25,137	Zyus'ko *et al.* 1993

The incubation time of round whitefish eggs decreases in response to increasing water temperature (Maher 1982). Incubation requires about 300 **degree days** (Normandeau 1969; McKinley 1983) and is reduced in warmer temperatures. Eggs collected from ripe fish on 1 December and reared in the laboratory at ambient Lake Ontario water temperatures, which ranged from 1.0 to 5.6°C, hatched between 5 and 13 April, at an average of 298 degree days (McKinley 1983). In Newfound Lake, New Hampshire, eggs laid in the first three weeks of December overwinter under the ice and hatch in April to May after about 123-140 days of incubation (~140 d @ ~2.2°C Normandeau 1969).

3.2 Young-of-the-year (Rearing habitat)

Round whitefish hatch as sac **fry** in March to May and remain on the bottom, seeking shelter in rubble and boulders (Normandeau 1969). At hatching they are about 12 mm long (Becker 1983; Shestakov 1991), and absorption of the yolk sac takes about 2 to 3 weeks (Morrow 1980).

In laboratory experiments, resting yolk sac larvae showed a significant preference (67%) for fine gravel substrate (0.3-0.5 mm) when given a range of substrates to choose from (i.e., 0.3-0.5 mm; 10-15 mm; 60-90 mm) (McKinley 1983, 1984). Their distribution was not influenced significantly by light level (range: darkness, 1.0 lux, 7-8 lux) or water motion. Their sustained swimming speed was 3.6±0.5 cm/s and, at any one time, the majority were swimming and within 10 cm of the substrate. Mortality was higher in current and with wave action, since more larvae were swept onto the downstream screens. Field sampling for **larval** whitefish may then be most effective using bottom sampling techniques over a sand bottom.

In Siberia young feed in the upper reaches of streams and along the shores of lakes (Kra'sikova 1968). Yolk sac larvae (12.1-15.4 mm) in Siberia's Anadyr River are passively dispersed downstream in late May through mid June, and larger larvae (mean body length 29.7-39.6 mm) continue to be dispersed downstream through July (Shestakov 1991, 1992). During their descent the larvae attempt to move into the shallows to begin feeding and further movement occurs along the shore. Juveniles in the Susitna River, Alaska, also move downstream to the lower river for rearing during their first year (Sundet and Wenger 1984).

In the Mackenzie Valley, round whitefish fry (25-33 mm fork length) were first taken from the confluence of Wolverine Creek and the Great Bear River on 26 June (Chang-Kue and Cameron 1980). Other nursery areas have been identified in the Willowlake River, Blackwater River, River Between Two Mountains and Hare Indian River (Doran 1974; McCart 1974; Lilley 1975), in Canyon and Vermillion creeks (Jessop and Lilley 1975), and in the Bell River (Shotton 1971). Suspected nursery habitats have been identified in the Ochre, Great Bear, Hanna, and Loon rivers (Doran 1974). In the northern Yukon fry have been found over gravel areas of streams soon after spring breakup (Bryan and Kato 1975).

Larval round whitefish in Alaska's Chena River were found in backwaters and shallow shoreline habitats, where water velocity was not strong enough to measure, over sand or mud substrates (Lee 1985). They stayed within 5 to 20 mm of the bottom, regardless of current, and used small drifts in the sand to shelter from current. Cover, in the form of vegetation, was sometimes present but was not used. As they increased in size the young-of-the-year moved into deeper water and faster current. Fish 15-34 mm in length (n = 22) were found at an average depth of 24.6 cm, and average water velocity of 4 cm/sec; fish 55-74 mm in length (n = 30) were found at an average depth of 40.0 cm and velocity water velocity of 24.1 cm/sec.

Older young-of-the-year in the Chena River were found mostly over silt substrates (90.9%; ≤ 0.1 cm; n=99), although some were found over rubble and cobble (6.1%; 8-30 cm), gravel (2.0%; 0.3-8 cm), or sand (1%; 0.1-0.3 cm) (Lee 1985). They are territorial in

the laboratory but tend to be subordinate to Arctic grayling (*Thymallus arcticus*) and chinook salmon (*Oncorhynchus tshawytscha*) fry. In **allopatric** situations all of the round whitefish (n=62) were found over silt substrate, while under **sympatric** conditions only 75% were found over silt, 16.2% over rubble and cobble, 5.4% over gravel, and 2.7% over sand.

3.3 Juveniles (Rearing habitat)

Older juveniles, age 1 and 2, live in the same areas as adults but in shallower water (Hale 1981). They tend to move into deeper and faster water as they grow (Lee 1985). Juvenile round whitefish (mostly age 0 and <200 mm) resident in Alaska's Susitna River were found most abundantly in mainstem side channels where they used high turbidity water (>30 NTU) for cover and showed strong preference for shallow water (<15 cm) without significant velocity (Suchanek *et al.*1984). They were captured to a depth of about 3 m.

3.4 Adults

The age of maturity of round whitefish varies geographically, and tends to be later in the north than in the south. Stein *et al.* (1973b) found that the minimum age of maturity of fish sampled in the Mackenzie River and its tributaries was age 8 (scale age). This is older than in most other areas of the Northwest Territories, including: Noell Lake north of Inuvik where the fish typically mature by age 6 (Read and Roberge 1986); Great Bear Lake, where females mature between the ages of 3 and 8 and males between ages 4 and 7 (scale age) (Kennedy 1949; Falk and Dahlke 1974; Dunn and Roberge 1989); the Great Bear River, where the youngest mature fish caught were aged 6 to 8 (scale age) (Chang-Kue and Cameron 1980); and Indin Lake where the youngest mature female was age 4 and the youngest mature male was age 5 (scale age) (Jessop *et al.* 1993).

In large lakes in the Kivalliq Region of Nunavut some round whitefish mature at age 4, and by age 8 most are mature (scale age; Roberge *et al.* 1984; Roberge and Dunn 1985). Round whitefish in seven Yukon lakes mature between the ages of 3 and 7 (scale age)(Horler *et al.* 1983), and those in the Delta Clearwater River, a tributary of Alaska's Tanana River, mature at age 6 or 7 and thereafter appear to spawn in consecutive years (Pearse 1974).

In Quebec's La Grande River round whitefish began maturing at age 3; by 4 at least 50% were mature; and by age 5 most were mature (scale age; Morin *et al.* 1982). In the Kokosak and George rivers of northern Quebec males mature between ages 4 to 7 y (scale age) and females at 3 to 6 y (MacKay and Power 1968). In the Leaf River of northern Quebec, both sexes matured at ages 4 to 6 y (scale and otolith age), but proportionately more females than males were mature at ages 4 and 5 y (Jessop and

Power 1973). Females matured at lengths of between 190-199 mm and 240-249 mm and males at lengths 10-20 mm greater, as in the Kokosak River (MacKay and Power 1968). Not all females spawned annually (Jessop and Power 1973).

Round whitefish in the Great Lakes, near the southern limit of their distribution, typically mature younger than those to the north, with some mature at age 2 to 3 (scale age) and all by age 6 (Bailey 1963; Mraz 1964; Armstrong *et al.* 1977; Haymes and Kolenosky 1984).

Individuals in northern populations appear to have a longer lifespan than those in the south, and latitude may be a more important determinant of growth rate than whether the population is riverine or lacustrine (Steinhart *et al.* 2007). However, round whitefish taken in lakes may be heavier at the same length than those in streams (Bendock 1980).

Individual round whitefish can live to at least age 20 (scale age; Macdougall Lake, NU--Moshenko 1980), fish over age 14 appear to be rare in the Mackenzie Valley. Round whitefish in Great Bear Lake can live at least 13 y (scale age) and grow to 483 mm **FL** and 1.6 kg **rdwt** (Falk and Dahlke 1974). Fish in Great Slave Lake can live to at least age 14 (scale age) and grow to 561 mm **TL** and 2.0 kg rdwt (Rawson 1951; Keleher 1961). The largest fish taken in the Rat River was 530 mm FL (Jessop *et al.* 1973). Fish in northern Quebec live to age 8 in the La Grande River (scale age; Morin *et al.* 1982), 12 in the Kokosak and George rivers (scale age; MacKay and Power 1968), and 14 in the Leaf River (scale age: Jessop 1972; Jessop and Power 1973). Round whitefish from the Kokosak and George rivers are slow growing and approach their maximum size at a constant rate, whereas those in the Great Lakes approach their upper size limit rapidly within the first 3 years and grow slowly thereafter (MacKay and Power 1968). The largest fish taken from Lake Michigan by Mraz (1964) and Armstrong *et al.* (1977) was 500 mm TL and age 8. The largest taken by Bailey (1963) from Lake Superior was 453 mm TL and age 11.

Otolith readings yield a higher age estimate than do scale readings for round whitefish over 6-8 y old, suggesting that the latter tend to underestimate the age of older fish (Jessop 1972; Morin *et al.* 1982; G. Steinhart, pers. comm. 2007). Magnin and Clément (1979) also found variations between scale and otolith readings, but the latter were not consistently higher. Otoliths are more difficult to read so most researchers have used scales.

Round whitefish in lakes are captured mostly in shallow water. In Great Slave Lake, Rawson (1951) captured them at depths of 2 to 35 m, but not in deeper samples (i.e., 36-300 m). In Great Bear Lake, Kennedy (1949) reported that they were scarce in the open lake and marshy bays, but common in non-marshy bays and river mouths with discernible current. They occur at least as deep as the **hypolimnion** in lakes in the

Kuskokwim River area of Alaska (Hale 1981). In Algonquin Park, ON, they occurred from the surface to at least 24 m depth in summer, but were most abundant between 6 and 12 m depth (Sandercock 1964). In the Great Lakes they were most abundant at depths <36.6 m (20 fathoms) and rare at depths >71.3 m (39 fathoms), (Koelz 1929; Becker 1983), although a fish has been taken in a net set at a depth of 218.9 m (Scott and Crossman 1973). In January and February catches of round whitefish along the coast of Lake Huron were 10 times greater at 5 m depth than at 12 m (Balesic 1983).

In Alaska's Tanana river system, round whitefish were caught most frequently in tributary mouth habitats that were distinguished from other habitats by their clear water and perennial flow (Mecum 1984). They were also caught in main and side channel habitats and in modified river habitats such as sloughs and dead-end side channels (i.e., groins). In the Alaskan interior, adult (>200 mm) round whitefish preferred deep pools in large streams with relatively low velocities (mean 17 cm/s) and coarse substrates, and selected for areas with channel widths greater than 10 m (Den Beste and McCart 1984). In streams on the North Slope of Alaska, they are found in summer over substrates ranging from silt to boulder, but most commonly over gravel bottoms (Hale 1981).

Adult round whitefish in Alaska's Susitna River used turbidity for cover and also used objects including (preferred to least preferred): cobble and boulder (>5"), undercut banks, overhanging vegetation, debris/deadfall, submergent vegetation, emergent vegetation, rubble (3-5") and large gravel (1-3") (Suchanek *et al.* 1984). At other streams in northern Alaska, depth was used as cover in most of the habitats observed during the summer, and cutbanks were present in nearly half of the round whitefish habitats observed (Den Beste and McCart 1984).

Round whitefish in streams on the North Slope of Alaska were found in stream gradients ranging from about 1.3 to 14.2 m/km (Kogl 1971). Current velocities in these streams ranged from about 24 to 274 cm/s, but the fish may not be present in the higher velocities. The critical velocity for nine round whitefish with an average fork length of 304 mm was 42.5 cm/sec (Hale 1981). While the species' distribution in the Susitna River of Alaska was not strongly tied to water velocity, fish did show preference for areas with water velocities ranging from 61 to 91 cm/s (Suchanek *et al.* 1984). In August-October, the contribution of round whitefish to the overall abundance of salmonids in Petite rivière de la Baleine (Little Whale River), QC, was greater in the rapids than in the river or estuary (Kemp *et al.* 1989).

In streams on the North Slope of Alaska, round whitefish are found in summer in water temperatures ranging from 3 to 16°C, at turbidities ranging from clear to 15 ppm (Hale 1981). In Algonquin Park, ON, they have been found at summer temperatures up to 22°C but were most common at temperatures ≤ 18°C (Sandercock 1964). Water

temperatures during the peak of the fall downstream migration in the Sagavanirktok River of Alaska ranged from 0 to 4°C (Yoshihara 1972).

Information on seasonal movements of adult round whitefish is limited. In a May to October tagging study at several Alaskan streams, most round whitefish were recaptured within 0.8 km of the tagging site, with the exception of one that traveled about 15.5 km downstream (Netsch 1975). However, a fish in the Susitna River moved about 114 km downstream (Sundet and Wegner 1984). In a July 9 to September 18 study of Alaska's Lupine River, no concerted upstream movement of round whitefish was observed but 37% of the fish moving downstream did so on the 3rd and 4th of September (Yoshihara 1972). Arctic grayling emigration from the system peaked at the same time. In the Great Lakes, fish may move inshore as the summer and fall progress, and also into tributary stream (Koelz 1929). Both of these types of movements may be associated with spawning.

Adult round whitefish have been found overwintering in deep holes in the Colville, Kuparuk, and Sagavanirktok rivers of Alaska at water temperatures of 0 to 1°C (Bendock 1977, 1980). In the Colville River, Alaska, apparently healthy fish with food in their stomachs were taken from 1°C water with dissolved oxygen concentrations ranging from 2.6 to 5.6 ppm (Bendock 1980). They have been observed overwintering in the Kuparuk and Sagavanirktok rivers of Alaska at oxygen levels ranging from 49 to 100% saturation (Bendock 1977). A "summer squeeze" may occur in some small lakes where warm surface waters and low oxygen at the bottom limit round whitefish feeding movements into the surface and bottom waters (G. Steinhart, Lake Superior State University, Sault Ste. Marie, MI, pers. comm. 2007).

Round whitefish will enter brackish water, and have been captured in salinities ranging from 2.2 to 19.2 ‰ in estuaries along the Quebec coast of James and Hudson bays (Morin *et al.* 1980; Morin and Dodson 1986). They are common in the estuaries of Grande rivière de la Baleine and Petite rivière de la Baleine on the Quebec coast of Hudson Bay (Le Jeune and Shooner 1982; St-Arneault *et al.* 1982), and sometimes enter nearshore waters of the Beaufort Sea (Bendock 1977).

Round whitefish prey opportunistically on small benthic organisms in shallow inshore waters of lakes, rivers, and estuaries (Stewart *et al.* 2007). Individuals may have distinct, albeit variable, search images (Steinhart *et al.* 2007). During the open water period, juveniles and adults eat a variety of aquatic insect larvae, pupae and nymphs, benthic molluscs, small crustaceans, fish eggs, and fish (Koelz 1929; Kennedy 1949; Rawson 1951; Sandercock 1964; Jessop *et al.* 1973, 1974, 1993; Stein *et al.* 1973b; Falk and Dahlke 1974; Armstrong *et al.* 1977; Magnin and Clément 1979; Chang-Kue and Cameron 1980; Chang-Kue *et al.* 1987; Merrick *et al.* 1992; Zyus'kov *et al.* 1993; Martin 2001). Young-of-the-year eat aquatic insect larvae and pupae (Jessop *et al.*

1974; Lee 1985), and likely eat small crustaceans as well. Fish in lakes may eat more molluscs and small crustaceans than those in rivers (Stewart *et al.* 2007). They may also move into streams to feed (McCart *et al.* 1972). Little is known of seasonal changes in the species' diet or about its winter diet.

The round whitefish's ability to exploit a range of benthic prey, as well as zooplankton and terrestrial drift, is likely one of the key factors that enables it to inhabit **oligotrophic** lakes across the Northwest Territories and Nunavut (Stewart *et al.* 2007). As a generalist feeder, it is likely a key link in food webs that lack the biological productivity to sustain more specialized feeders.

Piscivorous fishes are likely the key predators on the round whitefish, which is seldom targeted for harvest (Stewart *et al.* 2007). In northern waters the eggs are likely eaten by suckers, burbot, and members of their own species, and the fish are eaten by lake trout, burbot and northern pike (Koelz 1929; Rawson 1951; Normandeau 1969). Intra- and inter-specific competition for food may limit round whitefish growth. Small crustaceans may contribute more to the species' diet in the absence of lake whitefish (*Coregonus clupeaformis*), and in early spring (Sandercock 1964; Stewart *et al.* 2007). The introduction of warm water predators such as smallmouth bass, yellow perch, and rainbow smelt can cause populations to decline (Steinhart *et al.* 2007; Weidel *et al.* 2007).

4.0 HABITAT IMPACTS ON FISH BIOLOGY

Activities with the potential to affect key aspects of round whitefish habitat and thereby the species' biology are discussed below and summarized in Table 5. Habitat degradation, habitat fragmentation, species introductions, and improved access are all aspects of development that could affect the species, and their effects might also be modified by climate change.

Because the round whitefish is not targeted for harvest by subsistence, commercial or sport fisheries few studies have been conducted on its vulnerability to stressors. Fortunately its preference for lake, river and larger stream (>10 m width) habitats, and its habit of spawning in the fall in either river or lake habitats limit its vulnerability somewhat. In New York State, the decline of this species in most Adirondack lakes has been linked to the introduction of non-indigenous and native-but-widely-introduced fishes, and to habitat degradation (Department of Environmental Conservation 1999; Steinhart *et al.* 2007).

Table 5. Some activities with the potential to affect key aspects of round whitefish habitat and their potential effects on the species.

Activity	Potential impact		
	Habitat	Species	Directly affected life stage(s)
• water removal • drainage alterations • seismic testing	• reduced groundwater flow • altered baseflow and ice and temperature regimes	• degradation, reduction or loss of some stream spawning habitat • increased winter mortality of eggs and possibly other life stages	• all
• construction of roadways, pads, and structures • stream crossings	• streambed alteration by removal or disturbance of sand, gravel, and cobble substrates • sediment mobilization • streambed destabilization	• egg, larval, fry and juvenile mortality from physical damage, exposure, loss of cover, sediment mobilization • degradation, reduction or loss of stream spawning habitat	• all
• logging • clearing for right-of-ways, camps, etc. • stream crossings	• inland clearing • loss of riparian and instream cover (i.e., shoreline, large woody debris) • altered hydrological regime with more abrupt runoff • warming, increased sediment inputs	• degradation of spawning and rearing habitat in streams • higher mortality rates for larvae and fry in streams	• all
• culvert installation for stream crossings • dam construction • in-stream construction	• flow impoundment • changes in seasonal flow regimes, water depth, water velocity • habitat fragmentation	• interruption of spawning migrations • inundation or dewatering of spawning areas • population extirpation • creation of new overwintering areas	• adults, mainly spawners
• road and right-of-way construction • population growth	• improved access to round whitefish habitat	• increased potential for species introductions	• all life stages by introductions
• contaminants releases	• chemical pollution • acidification	• reduction in fish quality • increased mortality	• all
• climate change	• changes in the temperature and precipitation regimes • warming	• decrease in suitable habitat at lower latitudes may not be offset by an increase in suitable habitat at higher latitudes • increasing competition and predation by warmer water species	• all

4.1 Habitat degradation

Round whitefish are vulnerable to lake acidification. Populations in the Adirondacks area of New York State were extirpated from all lakes experiencing a pH of less than 5.5 (Steinhart *et al.* 2007). This correlation supports acidification as the ultimate cause of the species' extirpation, although other proximate factors may also have been involved.

For most of their long incubation period round whitefish eggs in northern waters are protected by ice cover. However, because spawning beds in rivers tend to be located in shallow areas with gravel to cobble bottom they may be attractive sites for obtaining construction materials. Disturbance of these sites or mobilization of upstream sediments could reduce reproductive success, as might slowing of the currents that keep the eggs clean and aerated at these sites, or altering water depth. Lake drawdowns may have contributed to the decline of round whitefish in several lakes in the Adirondacks of New York by exposing the species' eggs (G. Steinhart, pers. comm. 2007).

Dietary accumulation of contaminants by the round whitefish is limited by their habit of feeding on aquatic invertebrates, often larvae and pupae, rather than on biota that are older, higher on the food chain, and exposed to both airborne and waterborne contaminants. Round whitefish will bioaccumulate polychlorinated biphenyls (PCBs) and dichlorodiphenyl trichloroethane (DDT) residues as they grow (Miller and Jude 1984). Likewise, fish in environments that have received mercury-laden industrial discharges will accumulate mercury in their flesh, but at a lower level than predatory species such as northern pike (*Esox lucius*) and lake trout (*Salvelinus namaycush*) (Moore and Sutherland 1980; Lafontaine 1994). In Russia, gonadal abnormalities have been observed in round whitefish exposed to high levels of anthropogenic pollution from mining and smelting operations (Chebotareva *et al.* 1996).

Round whitefish from lakes in a watershed containing uranium mining and milling operations at Elliot Lake, Ontario, concentrated radionuclides (^{226}Ra, ^{210}Pb, ^{210}Po) in their bones and flesh (Clulow *et al.* 1998a+b). The activity levels of the radioactive materials in the fish tissues was low but regular monitoring of ^{210}Pb levels in the fish flesh was recommended from watersheds containing uranium operations.

4.2 Habitat fragmentation

The effects of habitat fragmentation on round whitefish may be limited somewhat by the species' ability to spawn in lakes and rivers. This flexibility may reduce the need for many populations to undertake concerted, long distance migrations of the sort undertaken by Arctic grayling, yellow walleye (*Sander vitreus*), and bull trout (*Salvelinus confluentus*). Together with its limited use of small tributary streams, this reduces the

vulnerability of these whitefish to activities that alter small stream channels or interrupt spawning migrations.

Flow impoundment could adversely affect spawning habitats within the impoundment and downstream by altering seasonal current and depth. It could also increase winter sedimentation and reduce egg survival, as it has done for lake whitefish (Fudge and Bodaly 1984).

4.3 Species introductions

Interactions with non-native species have contributed to the decline of round whitefish populations in lakes in the Adirondacks of New York State (Department of Environmental Conservation 1999; Steinhart *et al.* 2007). While some round whitefish populations managed to cope with introduced species, the number of predatory warm water fish species present is an important determinant of whether lakes continue to support round whitefish (Steinhart *et al.* 2007). The appearance of smallmouth bass (*Micropterus dolomieu*), rainbow smelt (*Osmerus mordax*), and yellow perch (*Perca flavescens*) has often accompanied a decline or disappearance of both round and lake whitefish. The detrimental effect of predator introduction was demonstrated at Little Moose Lake, where the number of small round whitefish (<200 mm TL) increased exponentially after a program was begun to remove introduced smallmouth bass (Steinhart *et al.* 2007; Weidel *et al.* 2007).

The introduction of fish and of invertebrates, such as the crayfish (*Oronectes limosus*) which may eat whitefish eggs (Normandeau 1969), should be avoided. In addition to increasing competition and/or predation, introduced species can alter fish populations by exposing indigenous populations to new parasites or diseases (Arthur *et al.* 1976).

4.4 Improved access

The likelihood of species introductions via the release of live bait, or by stocking, increases as access improves. Incidental harvests of round whitefish may also increase, but this is unlikely to result in overharvesting since the species is seldom targeted by fisheries (Miller 1947; Scott and Crossman 1973; McCart and Den Beste 1979). It is typically less abundant and smaller than the lake whitefish, which is harvested instead, and because individuals sometimes contain cysts of the parasite *Triaenophorus crassus* in their flesh (Miller 1947; Scott and Crossman 1973; Stewart and Bernier 1999). Round whitefish are caught incidentally in gill nets during fisheries targeting other species, but do not follow a lead readily so they are seldom taken in pound or trap nets (Koelz 1929). Because of their smaller average size, preference for living in deeper water, and habit of feeding on small, bottom-dwelling invertebrate species, round whitefish are caught less

frequently by angling than are lake whitefish (Department of Environmental Conservation 1999). The round whitefish is not predictably available in large numbers at rivers or small streams in the way that makes species such as Arctic grayling, Dolly Varden (*Salvelinus malma*), and walleye so vulnerable to overharvesting.

4.5 Climate change

Because the round whitefish frequents lakes, rivers and larger streams it may be better insulated from the physical effects of climate change than species that rely on smaller tributaries. Indeed, it might benefit from increases in invertebrate production. However, its current distribution suggests that some factor, or combination of factors, may limit its reproductive success or survival in warmer southern waters, particularly rivers and streams. Predation of eggs and fry by species such as the yellow perch could be an important factor. Another factor might be water temperature.

Unstable thermal regimes during egg incubation affect the survival of round whitefish eggs, which are sensitive to elevated temperatures during incubation (Griffiths 1980 cited in Haymes and Kolenosky 1984). Consequently, the species has been used as an indicator of the potential impact of a sinking thermal plume on fall-spawning species. Egg incubation times were strongly influenced by the warm-water plume from the Pickering Nuclear Generating Station (Maher 1982). Hatch dates were advanced by 1 to 40 days, with those closest to the discharge hatching earliest. Egg survival was also lower in areas that were influenced by the plume more often during the hatching period. Warmer, less stable water temperatures resulting from climate change might adversely affect round whitefish populations.

Any decreases in suitable habitat in the south may not be offset by increases in the north, since the species distribution already extends to the Arctic coast in most areas, and may be prevented by high salinities from moving to the Arctic Islands.

5.0 SUMMARY

While the round whitefish is widely distributed in northern waters, it remains one of the least studied of the coregonines due in part to its slow growth and small average size, which limit its commercial value. There are significant gaps in the knowledge of its general biology and habitat requirements.

The species shows lacustrine, adfluvial, fluvial, and anadromous life history types. In the southern part of its distribution, it is usually found in shallower areas of deep lakes, and in northern parts may also be found in rivers and streams. Seasonal movements may occur related to feeding in tributaries and estuaries, and fall spawning.

It is common in cold, clear water (0 to 18°C) above 37 m depth, but sometimes uses turbidity for cover. It is rarely taken below 71 m depth. Depth, substrates, undercut banks, and vegetation may also be used for cover. Juveniles and adults occur over silt to boulder substrates but are most common over gravel. They show preference for areas with discernible currents (<91 cm/s).

Round whitefish in the north mature later than those in the south, males at age 4 to 7 and females at age 3 to 8. They also tend to live longer, with most populations reaching ages of 14 to 20 (scale). Individuals spawn more than once following maturity but not necessarily every year. Spawning in large lakes and northern rivers in the Mackenzie Valley likely occurs earlier in the season (July-September) than in the south of the valley (October- November). It occurs over gravel to cobble bottoms in shallow areas of lake shores (0.15-15 m deep) or streams (0.52-1.5 m deep) with discernable currents (<100 cm/s) at water temperatures of >0 to 2.5°C. Fecundity ranges from about 1,000 to 25,000 eggs/female, and may average between 5,000 and 12,000 eggs/ female. No nest is built, and eggs are broadcast over the substrate and then abandoned. Incubation occurs at temperatures of about 0.6 to 5.6°C and takes about 300 degree days. Spawning locations have not been identified in the Mackenzie Valley.

Young hatch as sac fry in March to May and seek shelter in the substrate. Some are carried passively by currents until they drift or swim into shallow to feed. They occupy the spawning grounds and later shallow shorelines (<0.7 m) and backwaters of lakes and rivers. Older juveniles move into deeper (<3 m) faster water but occupy shallower lake habitat than the adults, and mainstem side channels of rivers. Their substrate preferences change from gravel to silt with growth, and they use turbidity and likely substrate for cover.

Round whitefish prey opportunistically on small benthic organisms in shallow inshore waters of lakes, rivers, and estuaries. Aquatic insect larvae, molluscs, small crustaceans, fish eggs and fish are the main food items. Intraspecific competition or interspecific competition from lake whitefish can reduce growth rates and alter habitat use. Piscivorous fishes are likely the species' key predators, since round whitefish are seldom targeted for harvest.

Few studies have been conducted on the species' vulnerability to stressors. Fortunately it prefers lake, river and larger stream (>10 m width) habitats, eats mostly aquatic invertebrates, and spawns in the fall in either river or lake habitats. These habits help to limit its vulnerability to habitat degradation, habitat fragmentation, harvesting, and climate change. However, its eggs are sensitive to elevated or unstable temperatures during incubation. It is vulnerable to lake acidification and absent from lakes with a pH of less than 5.5. And, the introduction of warm water predators such as smallmouth bass, yellow perch, and rainbow smelt can cause populations to decline.

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8.0 ABBREVIATIONS

FL = fork length—distance from the tip of the fish's snout to the notch in its tail.

NTU = Nephelometric turbidity units or NTU are a measure of light scattered by suspended particles in water. High NTU measurements indicate low water clarity (i.e. high turbidity).

TL = total length—distance from the tip of the fish's snout to the tip of its tail.

rdwt = round or intact weight

9.0 GLOSSARY

Adfluvial fish populations move between lake and river or stream environments.

Allopatric fish species do not inhabit the same waterbody.

Anadromous fish populations undertake move downstream into marine waters to feed, and return upstream into fresh water to spawn and/or overwinter.

Degree days are Centigrade degree days above 0°C (= Temperature units).

Fluvial fish populations remain in rivers and streams throughout their lives.

Fry are young fish, newly hatched, after yolk has been used up and active feeding has commenced.

The **hypolimnion** is the bottom water layer in a thermally stratified lake.

Iteroparous fish spawn more than once in their lives.

Lacustrine populations remain in lakes throughout their lives.

Larval fishes (plural larvae) are young fish, newly hatched, before the yolk has been used up.

Sympatric species occur in the same or overlapping areas.

Appendix 1. Life history and habitat parameters

The emphasis of this work is on observations from within the Mackenzie Valley region. Terms such as "dominant", "preferred" and "optimum", which have been used in other summaries (e.g., Ford *et al.* 1995; Roberge *et al.* 2002), are avoided unless they are supported by directed research studies. This is because sampling observations may not accurately reflect a species' preferences unless the spatial and temporal biases related to sampling design and gear are carefully controlled. The following sections define what is meant by the various life history and habitat use parameters used in the text and tables and in the appendices that follow. Some parameters described here may not be used in this report because this description applies to all of the habitat use reports in the series.

TABLES 2 and 3

Habitat use and requirements

These tables summarize habitat associations during the life history stages of the species. Separate tables may be included for stream, river, and lake environments. Observations from areas within the Mackenzie River watershed are in bold type. The following parameters are included, with the units of measurement typically used:

- **Habitat type** – habitat type most commonly associated with observations of the life history stage (e.g., streams--pools, runs, riffles; lakes--littoral, pelagic, benthic);
- **Stream gradient** – percent (%) slope;
- **Depth range (m)** – range of depths from which the species has been reported;
- **Substrate** – substrate type(s) most commonly associated with observations of the species;
- **Cover** – cover type(s) most commonly associated with observations of the species;
- **Habit** – typical distribution within the habitat type (e.g., surface, midwater, benthic, above or below thermocline, inshore or offshore);
- **Velocity range** – water velocities (cm/s) wherein the species is most commonly observed;
- **Turbidity (NTU or ppm):**
  - **range** – turbidity range wherein the species has been reported;
  - **limits** – upper and lower lethal limits as tested experimentally;
- **Oxygen (ppm):**
  - **range** – dissolved oxygen levels wherein the species has been reported;
  - **limits** – upper and lower lethal limits as tested experimentally;
- **Temperature (°C):**
  - **range** – water temperatures wherein the species has been reported;
  - **limits** – upper and lower lethal limits as tested experimentally;
- **Prey:**
  - **Primary** – taxa or taxon typically comprising the majority (by weight/volume/food value) of the food found in the stomachs of fishes sampled, or that were seen to be eaten during *in situ* behavioural studies;
  - **Secondary** – taxa or taxon comprising the minority (by weight/volume/food value) of food found in the stomach of fish sampled, or that were seen to be eaten during *in situ* behavioural studies. [Note: Differences in prey selection (i.e., primary/secondary) may reflect changes in the seasonal availability rather than the relative importance of food items.];
- **Duration** – number of seasons, months, or years in which each specific life stage exists or occurs;
- **Size/Age range** – average and/or maximum size range (mm) of the life history stage; or maximum size range (mm); FL = fork length, SL = standard length, TL = total length. A fish is age 0 until December 31 of the year it was hatched unless otherwise indicated.

Reproduction

This table summarizes habitat and life history parameters related to the species' reproduction. Observations from areas outside the Mackenzie River watershed are italicized. The following parameters are included:

- **Reproductive strategy** – *oviparous* species produce eggs that hatch outside the body of the mother; *iteroparous* species produce their young in annual or seasonal batches (most fishes); *semeloparous* species (e.g., salmon) produce all of their offspring at one time and then usually die; *annual* spawners reproduce each year following maturity until they die or reach reproductive senescence; under marginal conditions a portion of the reproductive population may rest for a year or more between spawning events (*% resting*);
- **Age at maturity** – range of ages at which males (M) and females (F) become sexually mature, with any estimate of the most common age at maturity provided in brackets;
- **Fecundity** – range in the number of eggs produced by females;
- **Spawning habitat** – habitat types wherein spawning has been observed, ripe and running fish have been caught, ripe and spent fish have been caught together, or eggs or sac larvae have been found. The presence of mobile young-of-the-year was used to identify nursery areas, and sometimes "suspected" spawning areas;
- **Spawning habit** – some species *build a nest* by altering the bottom substrates to meet their requirements before spawning; others *use existing nests* constructed by other species; *broadcast spawners* spread their eggs over suitable areas of unaltered bottom substrates; some species *care for the eggs* or *care for the young*;
- **Spawning temperature** – temperature range at which spawning has been observed;
- **Spawning depth** – depth range at which spawning has been observed;
- **Spawning substrate** – substrate type(s) observed at spawning locations;
- **Spawning current velocity** – current velocity observed at spawning locations;
- **Maximum age** – life expectancy of the species;
- **Reproductive senescence** – age at which the species stops reproducing.

APPENDICES 2 and 3

The seasonal habitat requirements for each life history stage are presented below in separate appendices for stream and lake environments. Within these appendices, observations from the Mackenzie River watershed are in bold type.

Life history stage

Observations on habitat use are summarized by life history stage. Four stages are recognized:

- **Spawning/eggs** – includes habitats on the spawning grounds where adults spawn and eggs mature and hatch;
- **Young of the year (YOY)** – larvae and fry less than age 1 (age 0 until December 31 of the year they are hatched);
- **Juveniles** – sexually immature fish older than age 1;
- **Adults** – include fish that have attained sexual maturity.

Seasons

Habitat use was divided into four seasons, which correspond to the environmental conditions rather than to the calendar seasons. Calendar months are also provided if possible, but the correspondence between environmental variables and calendar months varies from south to north and from year to year. In the north of the Mackenzie watershed (Inuvik; S. Stephenson, DFO, pers. comm.), the seasons used are:

- **Spring (Sp)** – the period of ice breakup and spring runoff, typically late April to mid June;
- **Summer (Su)** – the period of open water, typically mid-June to late September;

- **Fall (Fa)** – the period of ice formation, typically late September to late November;
- **Winter (Wi)** – the period of ice cover, typically late November to late April.

In the south (Hay River; G. Low, DFO, pers. comm.) they are:

- **Spring (Sp)** – the period of ice breakup and spring runoff, mid-April to early June;
- **Summer (Su)** – the period of open water, typically early June to late-September;
- **Fall (Fa)** – the period of ice formation, typically late-September to mid-November;
- **Winter (Wi)** – the period of ice cover, typically mid-November to mid-April.

These date ranges are averages, since the timing of breakup varies from river to river and lake to lake depending upon factors such as stream gradient, exposure to sunlight, and lake size.

Water depth

Five water depth categories area used for stream environments: 0–0.2, >0.2–0.6, >0.6–1, >1–2, and >2 m. Depth represents the distance from the surface of the water downwards. The depth association of a fish found in the upper metre of the water column, for example, would be reported as 0–0.2, >0.2–0.6 and >0.6–1.0. Depth is reported as stated in the reference, but if "shallow" water was the only descriptor, a depth of 0–20 cm was used to represent "shallow" water. A broader range of depths is used to describe lake environments: 0–1, >1–2, >2–5, >5–10, and >10 m.

Substrate type

Substrate type was reported as stated in the reference. However, if particle size was provided, substrate type was classified as follows:

- **bedrock** = uniform continuous substrate;
- **boulder** = >25 cm;
- **cobble** = 17–<25 cm;
- **rubble** = 6.4–<17 cm;
- **gravel** = 0.2–<6.4 cm;
- **sand** = <0.2 cm;
- **silt/clay** = finer than sand with fine organic content;
- **muck (detritus)** = mud with coarse organic content;
- **hard-pan clay** = clay; and
- **pelagic** = open water.

Cover type

Cover features that may provide protection, or a refuge, from predators, competitors, and adverse environmental conditions include:

- **None** – no cover;
- **Submergent vegetation** – aquatic plants that grow entirely below the surface and are attached to the bottom by roots or rhizomes;
- **Emergent vegetation** – aquatic plants with foliage that is partly or entirely borne above the water surface (e.g., cattail *Typha* spp.) or float on the surface of the water (e.g., milfoil);
- **Algae** – aquatic algae present on the bottom or within the water column;
- **Wood** – large (LWD) or smaller woody debris (SWD) on the bottom or within the water;
- ***In situ*** – submerged cavities and/or crevices, undercut banks;
- **Substrate** – interstitial spaces between any size of substrate (boulder-sand);
- **Overhead** – cover originating outside the riparian zone that overhangs the stream and/or banks, which includes overhanging banks or riparian vegetation, woody debris outside the channel, or anything above the surface that provides shade.

Habitat

In flowing water, habitat refers to the type of channel unit, and typical water velocity within the unit that the species inhabits, including:

- **Pool** – velocity range $<0.25\ m{\cdot}s^{-1}$;
- **Run** – velocity range $0.25 – 0.50\ m{\cdot}s^{-1}$;
- **Riffle** – velocity range $0.50 – 1.00\ m{\cdot}s^{-1}$;
- **Rapid** – velocity range $>1.00\ m{\cdot}s^{-1}$;
- **River margin** – habitat along the banks of the mainstem channel, often low velocity;
- **Off-channel** – any habitat that is outside the mainstem flow including side channels, backwaters, and off channel habitats, often low or no velocity.

Water velocity differences are not used to differentiate lake habitats; rather they are differentiated on the basis of their proximity to flowing water or shorelines, as follows:

- **Lake inlet** – near or within stream or river plumes entering the lake;
- **Lake outlet** – near or within the channel that drains the lake;
- **Inshore** – typically associated with littoral habitat along the edges, rather than the middle of the lake;
- **Offshore** – typically associated with the middle, rather than the edges of the lake. Where possible their typical position in the water column is described (e.g., surface, midwater, benthic, above or below thermocline).

Appendix 2. River habitat requirements for round whitefish.

Stream habitat features:	LIFE STAGES [Season of use (reference)]				LEGEND/COMMENTS/REFERENCES
	Spawn/egg	YOY	Juvenile	Adult	
Depth (m)					
0-0.2			Su (1)		**Season of use:**
>0.2-0.6	Fa (1)		Su (1)		Sp = spring
>0.6-1	Fa (1)		Su (1)		Su = summer
>1-2	Fa (1, 2)		Su (1)		Fa = fall
>2			Su (1)		Wi = winter
Substrate					
Bedrock					
Boulder	Fa (1)			Su (8)	
Cobble	Fa (1, 2)	Su (4)		Su (8)	
Rubble	Fa (1, 2)	Su (4)		Su (8)	
Gravel	Fa (1*, 2)	Sp (3)		Su (8**)	*May use areas with groundwater inflow, Adults most common in streams with gravel bottom.
Sand	Fa (2)	Su (4)		Su (8)	
Silt/Clay	Fa (1)	Su (4*)		Su (8)	*Most older YOY found over silt.
Muck (Detritus)					
Hard-pan clay					
Pelagic					
Cover					
None		Sp (4*)			*Vegetation sometimes present but not used.
Submergents				Su (1)	
Emergents				Su (1)	
Algae					
Wood				Su (1)	
In situ					
Substrate				Su (1)	
Undercut bank/overhang				Su (1,5)	
Overhead				Su (1)	
Other*			Su (1*)	Su (1*,5**)	* Turbidity, **Depth
Velocity/Habitat	Fa (1*)			Su (5**,6*)	* Mainstem or tributary mouths, **Channel widths greater than 10 m.
Pool	Fa (1,2)		Su (1)	Su (5), Wi (7)	
Run	Fa (1,2)				
Riffle	Fa (1,2)			Su (1)	
Rapid					
River Margin					
Off-channel				Su (6)	

1 = Suchanek *et al.* 1984—Susitna River, Alaska
2 = Zyus'ko *et al.* 1993—Torgo River, Siberia
3 = Bryan and Kato, 1975--Aishihik Lake, Yukon
4 = Lee 1985—Chena River, Alaska
5 = Den Beste and McCart 1984—Alaskan interior rivers
6 = Mecum 1984—Tanana River, Alaska
7 = Hale 1981—Review Alaska

Appendix 3. Lake habitat requirements for round whitefish. Data from the Northwest Territories are in bold type.

Lake habitat features:	LIFE STAGE [Season of use (reference number)]				LEGEND/COMMENTS/REFERENCES
	Spawn/egg	**YOY**	**Juvenile**	**Adult**	
Depth (m)					
0-1	Fa (1)				Note: Spawning appears to occur in summer (Su) in the northern Mackenzie watershed. *The New Hampshire and Great Lakes observations (2-5) were from November and December (i.e., Wi), but the conditions more closely resemble those of the fall (Fa) in the north
>1-2	Fa (1, 2*)				
>2-5	Fa (1, 2-5*)				
>5-10	Fa (3-5*)				
>10	Fa (3*)				
Substrate					
Bedrock	Fa (1)				
Boulder	Fa (1)	Sp (2)			
Cobble	Fa (1)	Sp (2)			
Rubble	Fa (1-3)	Sp (2)			
Gravel	Fa (1-3)	Sp (1)			
Sand	Fa (1)				
Silt/Clay	Fa (1*)				*Spawned over silt and *Potomogeton* .
Muck (Detritus)					
Hard-pan clay					
Pelagic					
Cover					**Season of use:**
None					Sp = spring
Submergents					Su = summer
Emergents					Fa = fall
Algae					Wi = winter
Wood					All = year-round
In situ					
Substrate		Sp (2)			
Undercut bank/overhang					
Overhead					
Other					
Habitat					
Lake inlet	Fa (3)				
Lake outlet	Fa (1*)			Su (6)	*Currents 31-63 cm/s.
Inshore (littoral)	Fa (1-5)			Su-Fa (3), **Wi** (7)	
Offshore-surface					
Offshore-midwater					
Offshore-benthic					

1 = Bryan and Kato 1975--Aishihik Lake, Yukon
2 = Normandeau 1969—Newfound Lake, New Hampshire
3 = Koelz 1929—Great Lakes
4 = Haymes and Kolenosky 1984—Lake Ontario
5 = Carey 1983—Lake Ontario
6 = Kennedy 1949—Great Bear Lake, Northwest Territories
7 = Balesic 1983—Lake Huron